

# Jet Results from DØ

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(for the DØ Collaboration)

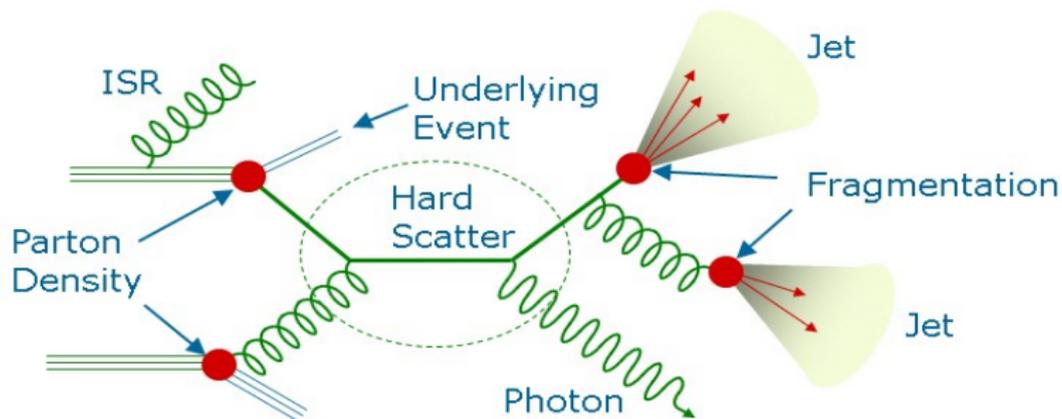
**Jets in Proton-Proton and Heavy Ion Collisions**  
**August 12-14, 2010, Prague**



- **Motivation for Jet Physics**
- **Tevatron and DØ Detector**
- **Jet Algorithm and Energy Scale**
- **DØ Results**
  - Inclusive Jets and  $\alpha_S$
  - Dijet and Multijet Final States
  - Vector Boson + Jets Final States
- **Conclusions**

# Motivation for Jet Measurements

- Test of perturbative QCD (LO/NLO calculations, PDFs,  $\alpha_S$ )
- Constrain of PDFs (high  $Q^2$ , medium to high  $x$ )
- Background to other SM processes or to new physics (SUSY,  $4^{th}$  generation, extra dimensions, ...)

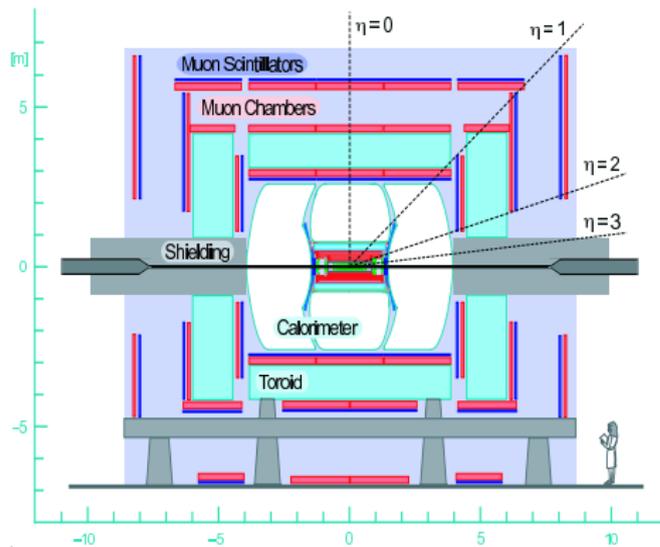


# Fermilab Laboratory and Tevatron Accelerator



- $\sqrt{s} = 1.96 \text{ TeV}$
- $36 \times 36 \text{ } p\bar{p}$  bunches,  $396 \text{ ns}$  bunch spacing
- Peak luminosity  $4.0 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Integrated luminosity  $\sim 8 \text{ fb}^{-1} / \text{experiment}$
- Scheduled to end in 2011

# DØ Detector

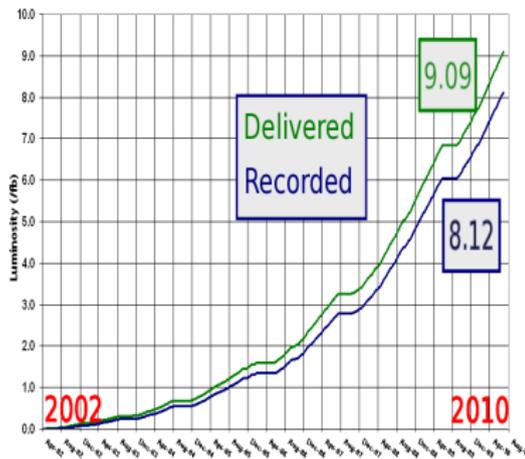


- Silicon and scintillating fiber tracking system in 2 T mag. field
- Uranium liquid argon calorimeter
- Muon system



Run II Integrated Luminosity

19 April 2002 - 10 July 2010



# Comparison of LHC and Tevatron

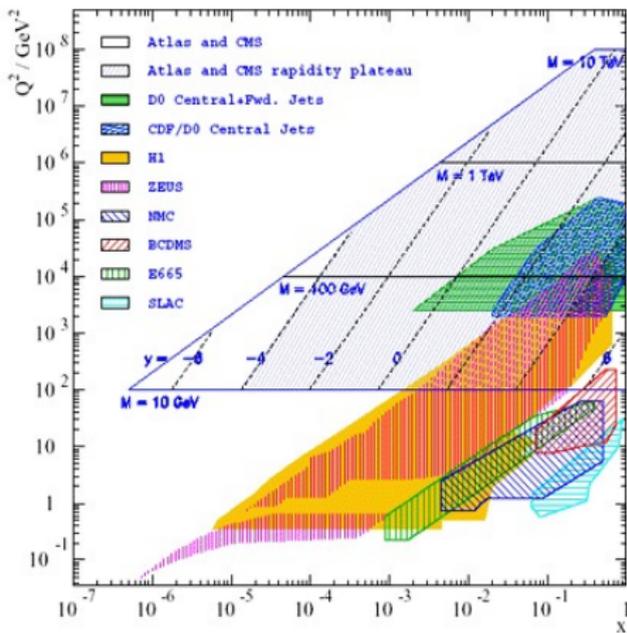
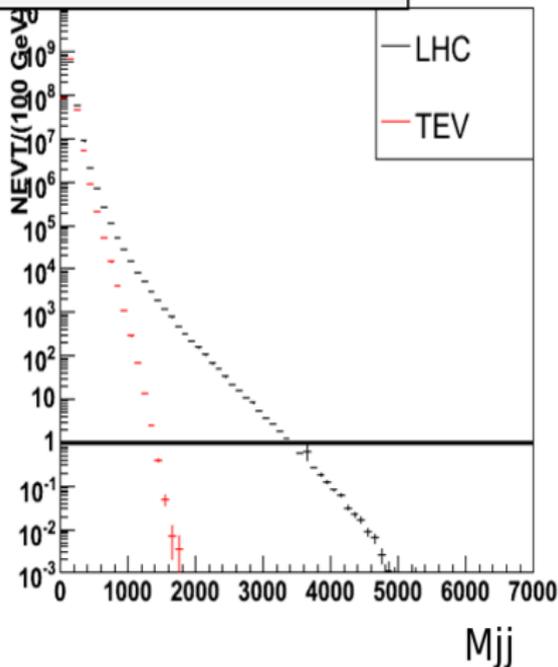


FIG. 1: Kinematic coverage of the DIS and collider  $pp$ - $p\bar{p}$  experiments. For  $pp$  and  $p-\bar{p}$  colliders, the Bjorken  $x_1$  and  $x_2$  of the interacting quarks are related to the mass  $M$  of the Drell-Yan pair and its rapidity  $y$  as  $x_{1,2} = M/\sqrt{S} \exp(\pm y)$  where  $S$  is the center of mass energy squared for the experiment.

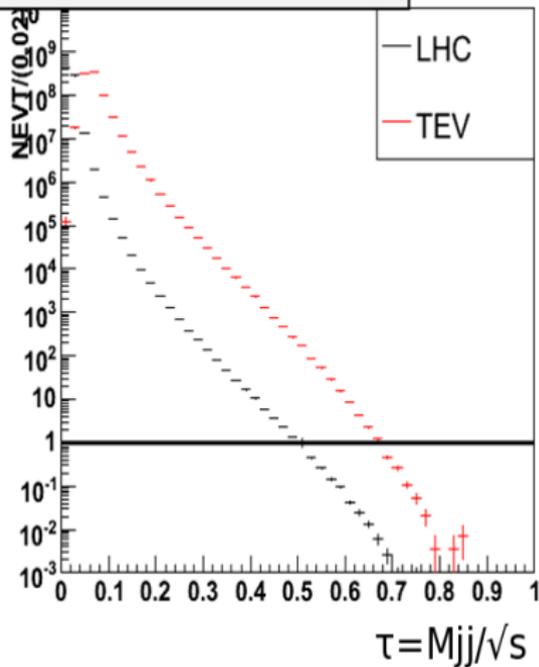
- $E_{CM}$  of 1.96 TeV vs 7(14) TeV - not always important (diphoton cross section differs only by a factor of 2)
- $p\bar{p}$  vs  $pp$  - Tevatron has better PDF sensitivity with a larger reach in  $x_T = \frac{2p_T}{\sqrt{s}}$  or  $\tau = \frac{M_{JJ}}{\sqrt{s}}$
- Integrated luminosity - at LHC shutdown, Tevatron will have 2x more events in  $\gamma$ +jets and  $Z$ +jets samples

# Comparison of LHC and Tevatron in Dijet Mass

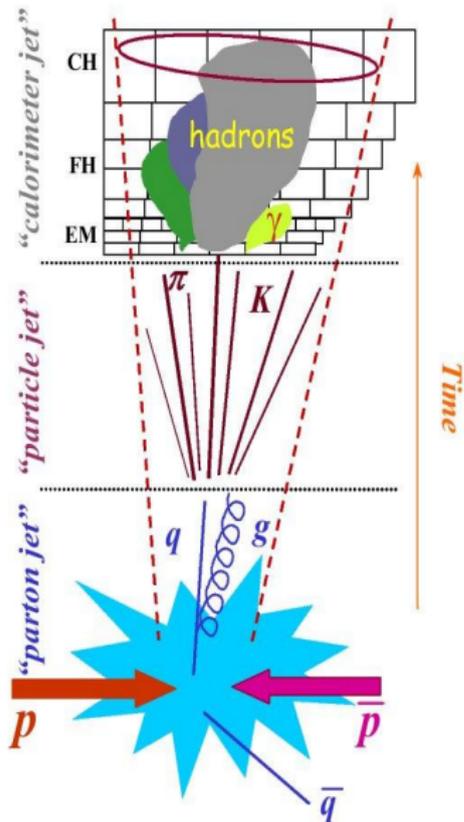
Overlay TeV(10fb-1) LHC(1fb-1)



Overlay TeV(10fb-1) LHC(1fb-1)



# Jets as Clusters of Objects



- Calorimeter jet

- interaction of hadrons with calorimeter
- collection of calorimeter cell energies

- Particle jet

- after hadronization and fragmentation
- effect of hadronization is soft  $\Rightarrow$  allows comparison between particle and parton jets

- Parton jet

- hard scattering
- additional showers

# DØ Jet Algorithm

Cone jet algorithm - arXiv:hep-ex/0005012:

DØ calorimeter is finely segmented -  $\sim 50000$  cells form  $\sim 5000$  calorimeter towers  $\Rightarrow$  preclusters (simple cones  $R = 0.3$ ) are used as seeds to reduce CPU time:

- 1 Iteratively find stable cones around all seeds:

$$R_{\text{cone}} = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.5 \text{ or } 0.7$$

- 2 Use **4-vector scheme** -  $p_T$  instead of  $E_T$ ,  $y$  instead of  $\eta$  (massive jets)
- 3 Add **midpoints** (between pairs of stable cones) and find stable cones around them to reduce IR and collinear safety
- 4 Treat overlapping jets - split-merge fraction 50%
- 5 Discard low  $p_T$  objects - minimum jet  $p_T$  6 GeV

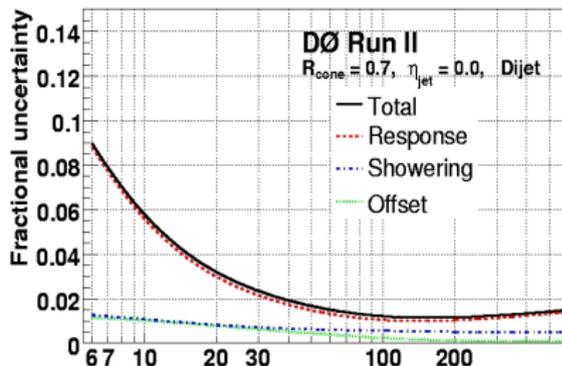
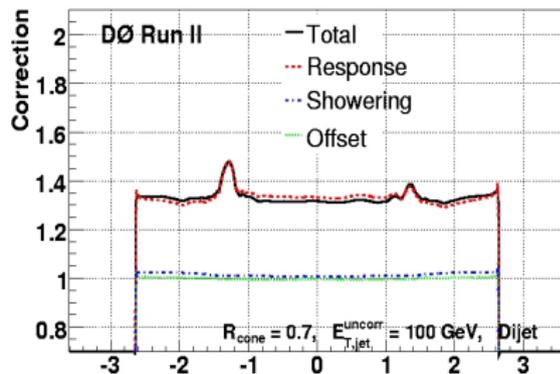
# Jet Energy Scale Calibration

Calibration to correct jet 4-vector to the particle level:

$$E^{\text{corr}} = \frac{E^{\text{meas}} - O}{R \cdot S}$$

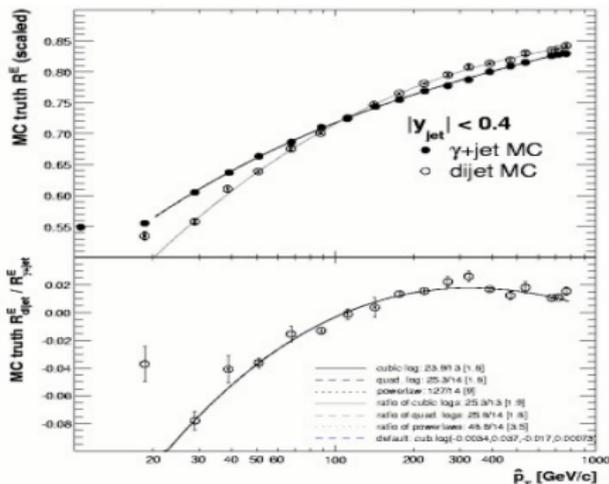
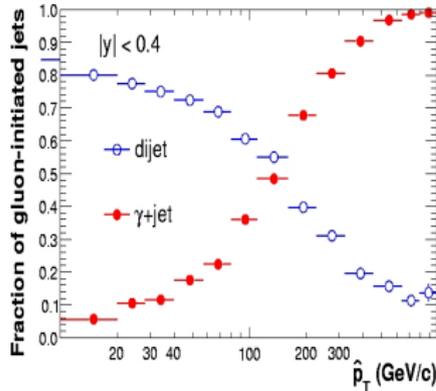
- Offset ( $O$ )
- Response ( $R$ )
- Showering ( $S$ )

7 years of extensive studies to reach the precision below 2%!



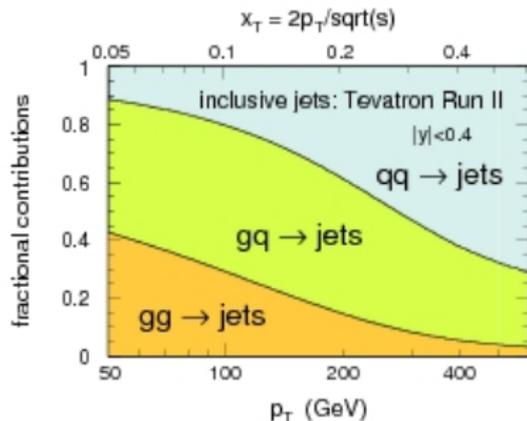
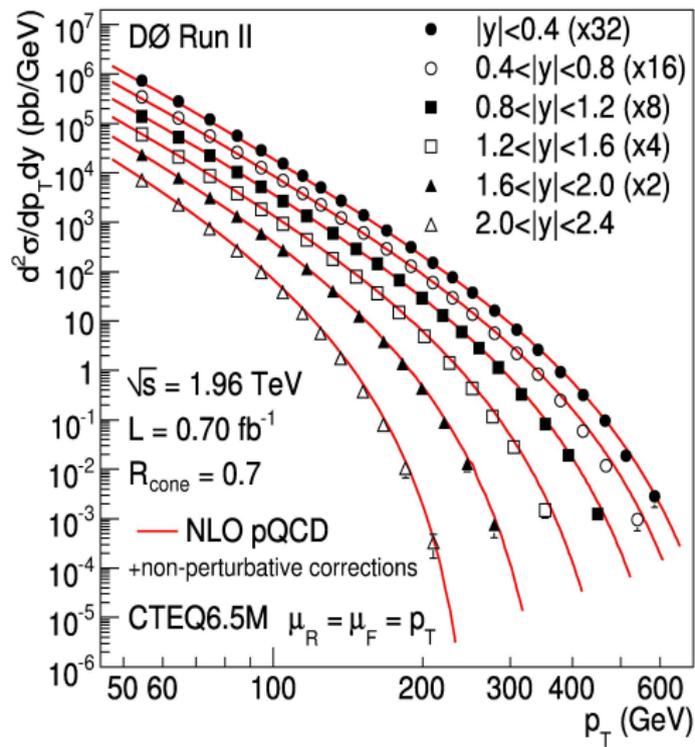
# Differences between quark and gluon responses

- Jet response is generally the largest subcorrection
- Different response for quark and gluon initiated jets - studied in  $\gamma$ +jet and dijet samples
- $\Rightarrow$  different corrections depending on physics - QCD jets (gluon dominated) vs  $t\bar{t}$  events (quark dominated)



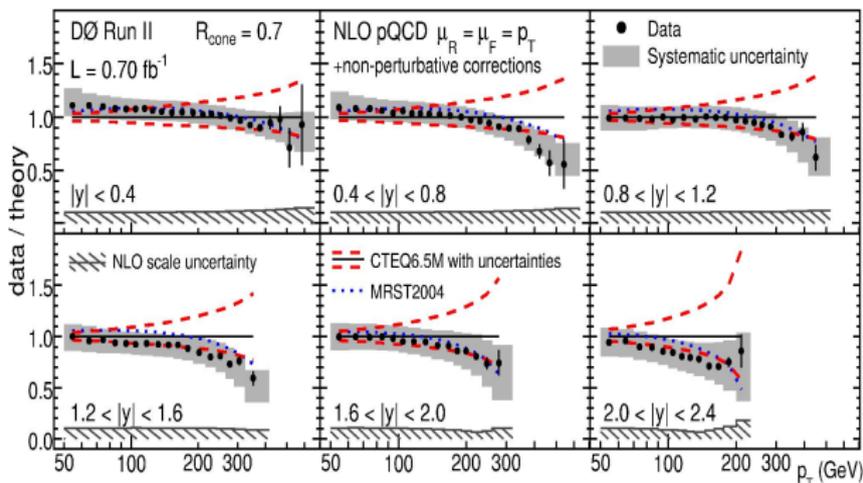
[http://www-d0.fnal.gov/phys\\_id/jes/public\\_RunIIa/](http://www-d0.fnal.gov/phys_id/jes/public_RunIIa/)

# Inclusive Jet Cross section



- Test of NLO QCD calculations over many orders of magnitude
- CTEQ6.5M PDFs
- PRL 101, 062001 (2008)

# Comparison with Theory

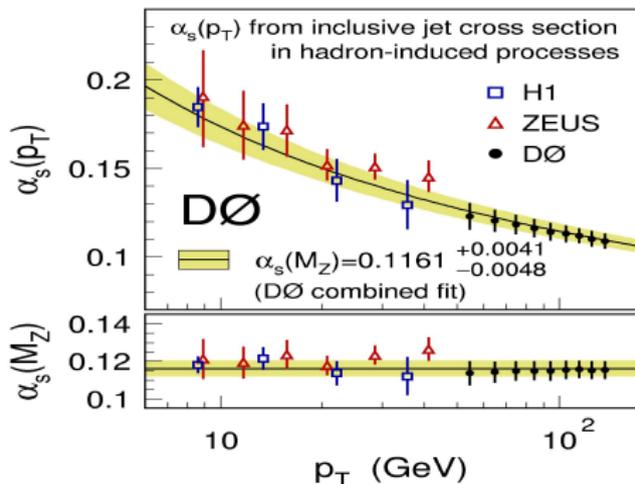


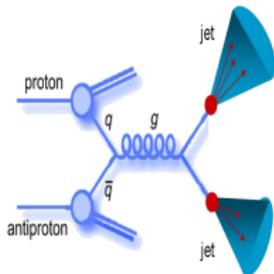
- Good agreement with NLO calculations
- Data favour lower bound of theoretical predictions with smaller gluon densities at high  $x$
- Full correlation between uncertainty sources available to further constrain the PDFs
- Data used in new PDF sets already - MSTW2008

# Strong Coupling Constant $\alpha_S$

- Inclusive jet cross section used to measure  $\alpha_S$   
$$\sigma_{\text{pert}}(\alpha_S) = \left(\sum_n \alpha_S^n c_n\right) \otimes f_1(\alpha_S) \otimes f_2(\alpha_S)$$
- $c_n$  known from NLO QCD
- MSTW2008 provides PDFs ( $f_1, f_2$ ) for 21 values of  $\alpha_S(M_Z)$
- Restrict analysis to kinematic region where Tevatron data does not dominate the PDFs

- Most precise determination of  $\alpha_S$  from a hadron collider  
$$\alpha_S(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$
- PRD 80, 111107 (2009)



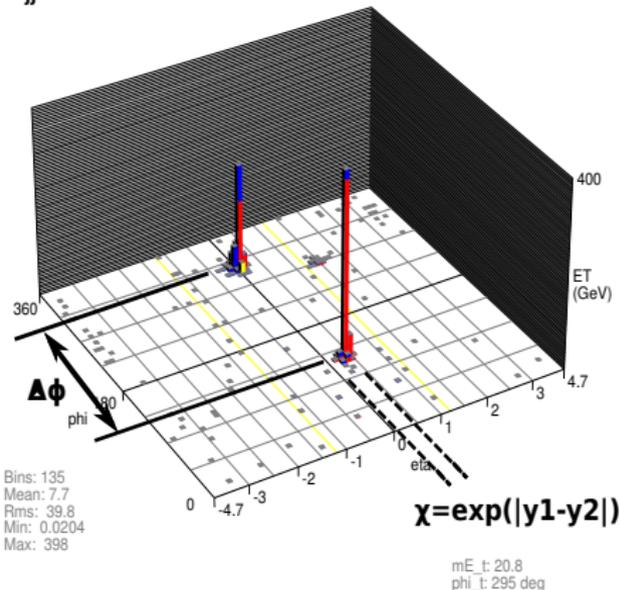


- Dijet invariant mass
- Angular variables -  $\chi$ ,  $\Delta\phi$

## Real dijet event display:

Run 174236 Event 9566856

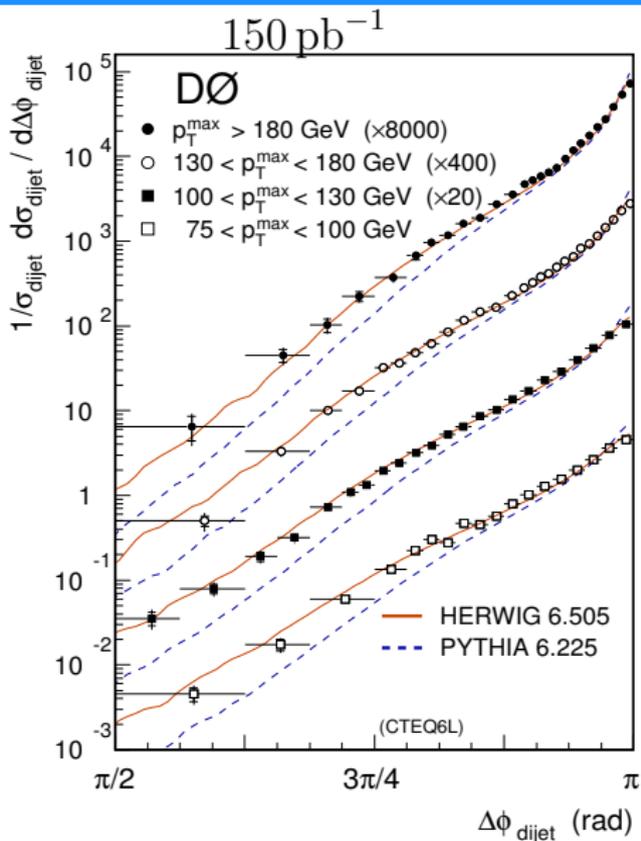
$$M_{jj} = (\mathbf{E1} + \mathbf{E2})^2 - (\mathbf{p1} + \mathbf{p2})^2$$



# Dijet Azimuthal Decorrelations

- Measure  $\Delta\phi$  between the two leading jets
- Dijet production in lowest order pQCD - jets have equal  $p_T$  and  $\Delta\phi_{\text{dijet}} = \pi$
- Additional radiation causes azimuthal decorrelations
- $\Delta\phi$  sensitive to higher order QCD radiation without measuring additional jets
- Sensitivity of MC parton shower models  $\rightarrow$  new MC tunes

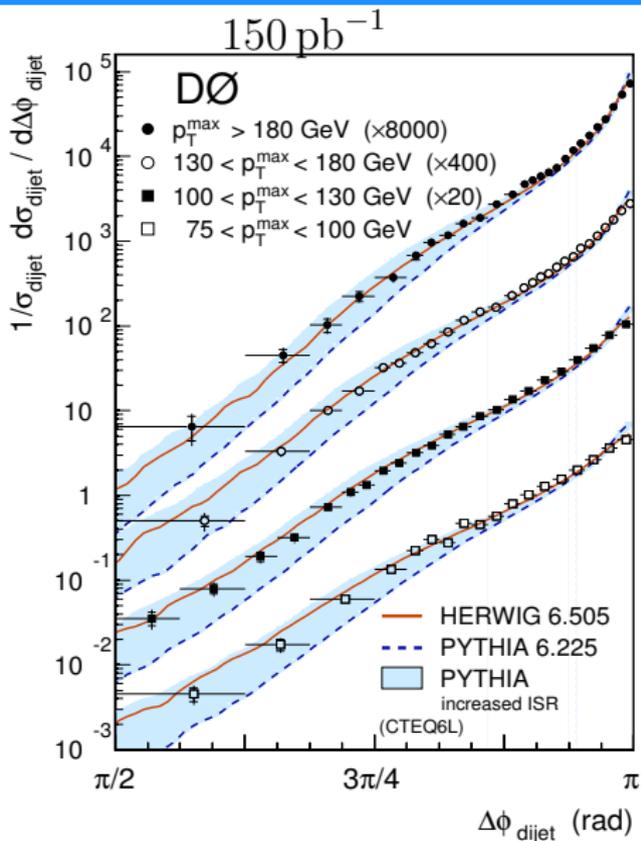
PRL 94, 221901(2005)



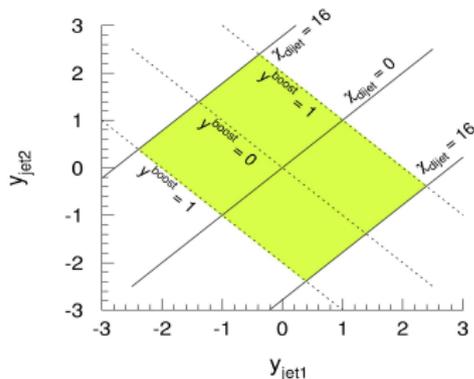
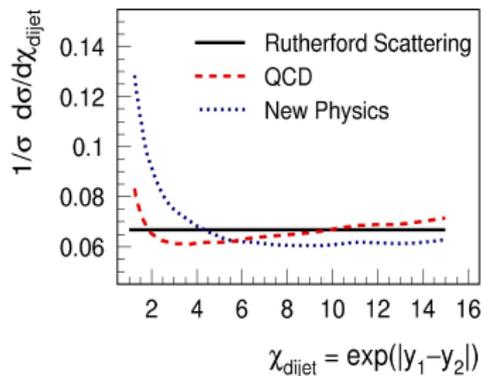
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PRL 94, 221901(2005)



# Dijet Angular Distribution - dijet $\chi$



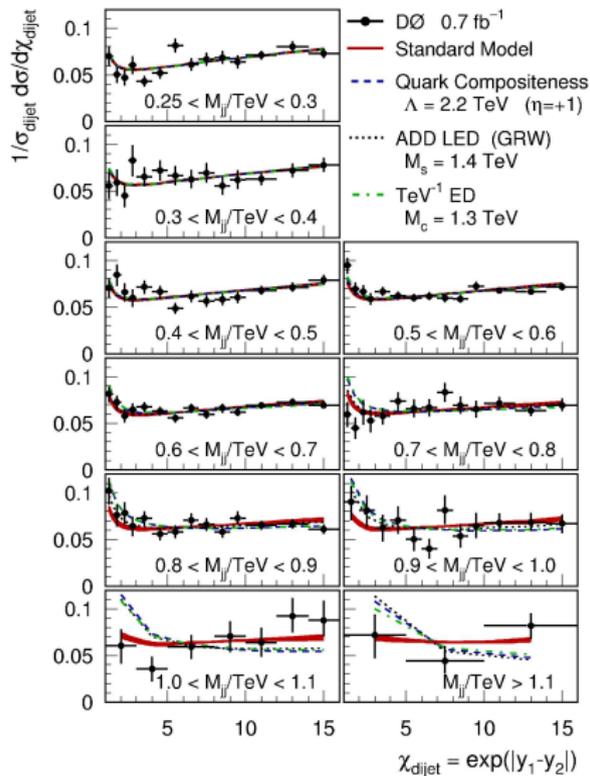
- Measure  $\chi = \exp(|y_1 - y_2|)$  in 10 regions of dijet invariant mass  $M_{JJ} > 0.25$  TeV for events with  $|y_{\text{jet}}| < 2.4$  and  $\chi < 16$  using  $0.7 \text{ fb}^{-1}$  data
- Compared with NLO pQCD + non-pert. corrections
- Used to set limits on new physics models

# Dijet Angular Distribution ( $\chi = \exp(|y_1 - y_2|)$ )

Best limits on new physics:

- Quark compositeness
- ADD Large extra dimensions
- $\text{TeV}^{-1}$  extra dimensions

PRL 103, 191803 (2009)

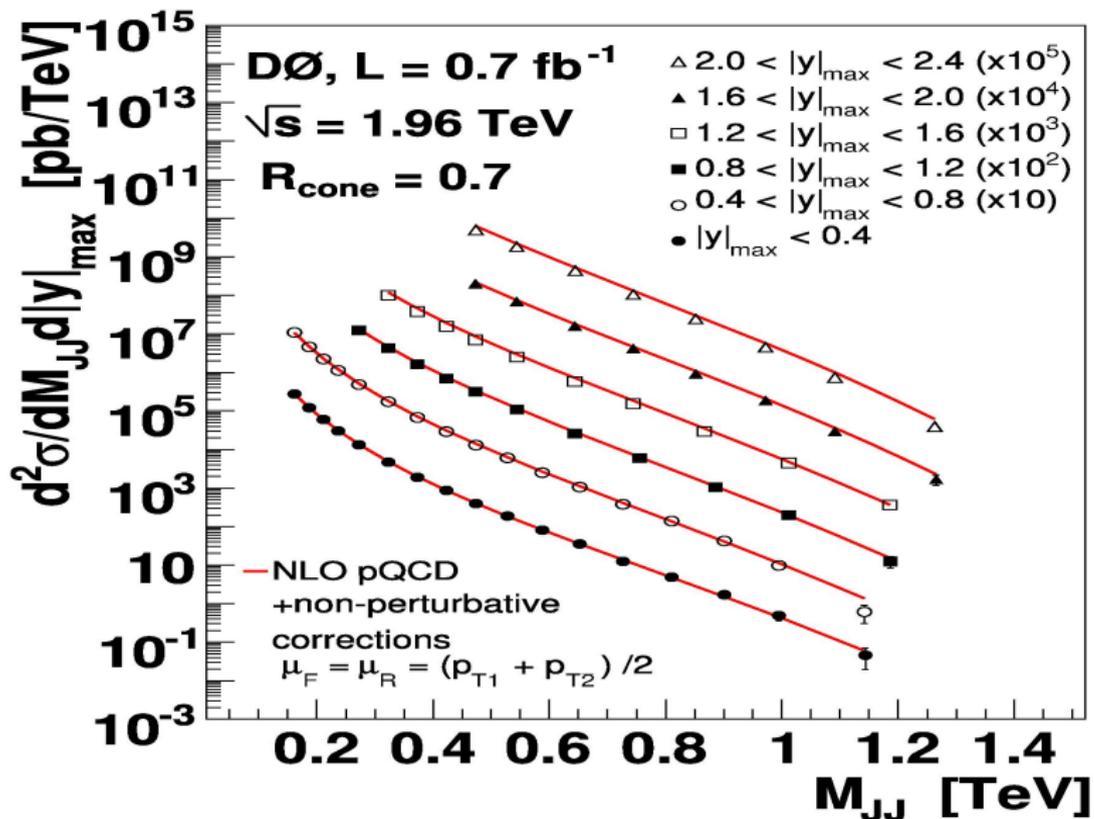


## Event selection:

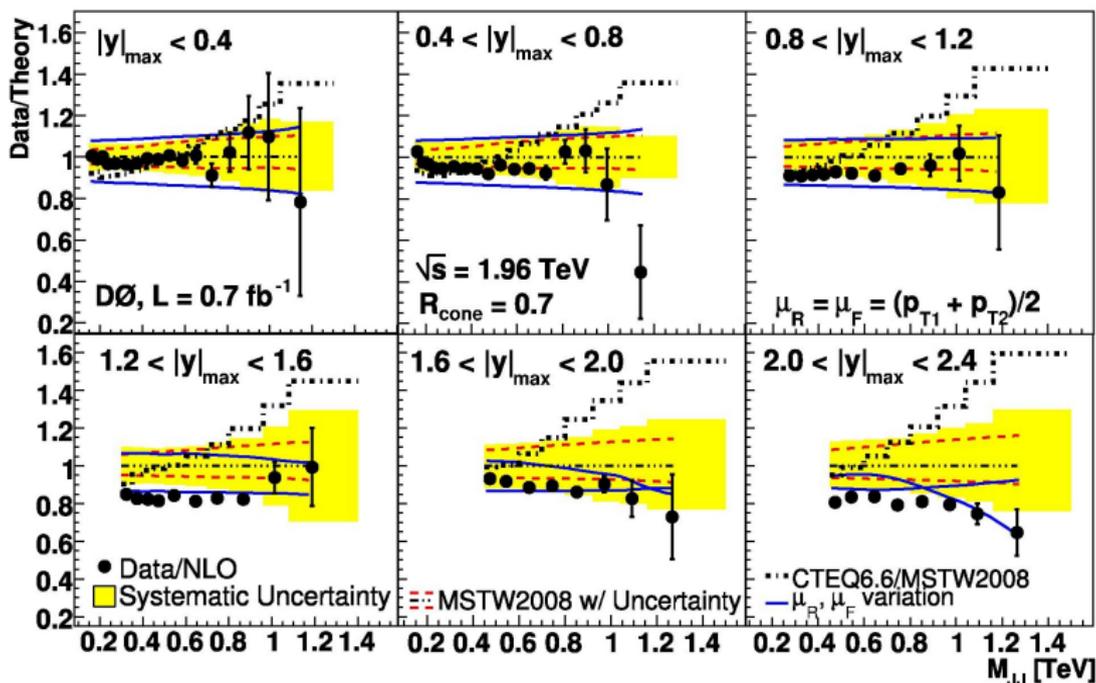
- $0.7 \text{ fb}^{-1}$  - well understood dataset
- At least 2 jets,  $p_T > 40 \text{ GeV}$
- 6 rapidity bins according to the most forward jet from  $|y|_{\text{max}} < 0.4$  to  $2.0 < |y|_{\text{max}} < 2.4$

arXiv: 1002.4594 (submitted to PLB)

# Dijet Mass



# Dijet Mass Comparison With Theory



- Note that MSTW2008 uses Run II data in PDF fits
- Good agreement in the central region
- 40 – 60% difference between MSTW2008 and CTEQ6.6

# Three-jet Final State

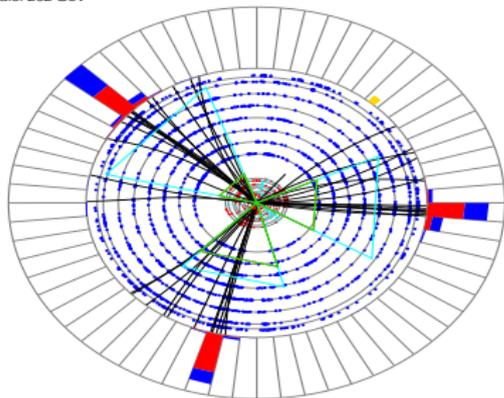
Topologically more complicated final state  $\Rightarrow$  more variables for possible study:

- Three-jet mass
- Angles
- Energy distribution among jets (Dalitz variables  $X_3, X_4$ )

Ratio of 3- to 2- jet cross section proportional to  $\alpha_S$

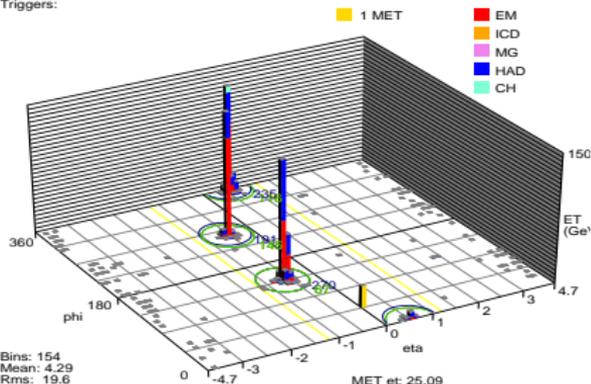
Run 204698 Evt 48041857

ET scale: 202 GeV



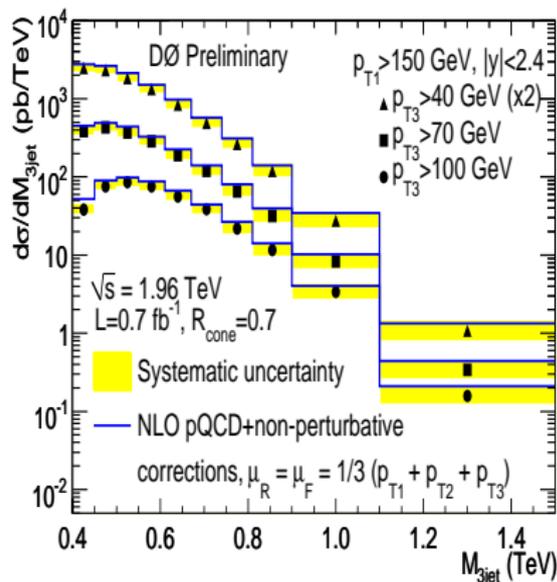
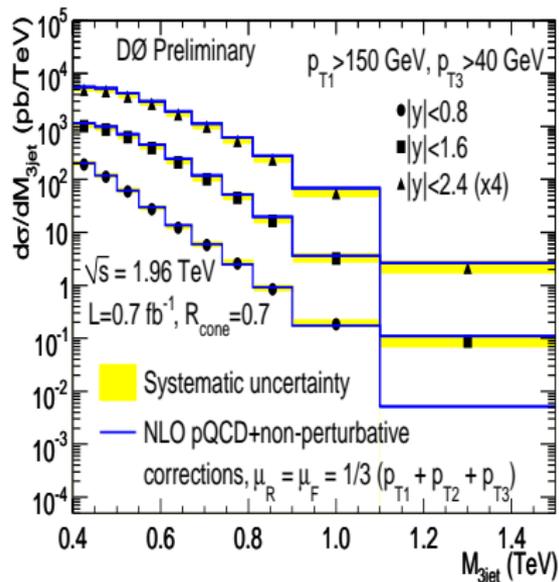
Run 204698 Evt 48041857

Triggers:

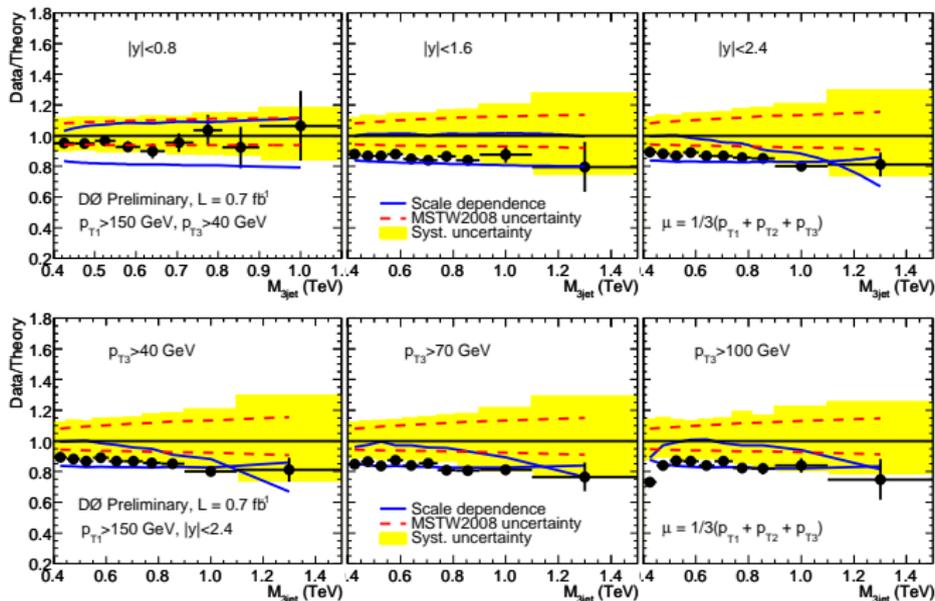


# Three-jet Cross Section

Differential measurement of three-jet mass:  $p_T^{\text{lead}} > 150 \text{ GeV}$ ,  
 $p_{T3} > 40 \text{ GeV}$ ,  $\Delta R_{jj} > 1.4$



# Three-jet Cross Section



- Reasonable agreement with NLO (MSTW2008)

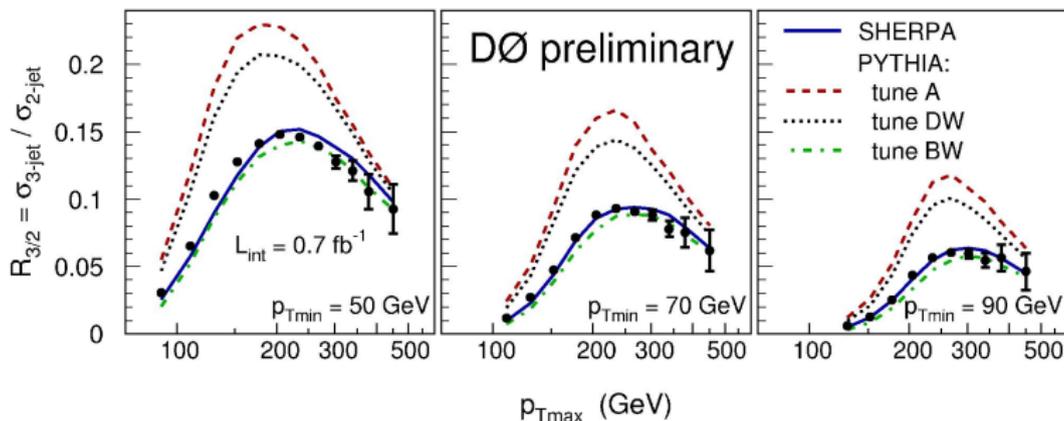
# R3/2 Measurement

$$R_{3/2} = P(3^{\text{rd}} \text{ jet} | 2 \text{ jets}) = \frac{\sigma_{3\text{-jet}}}{\sigma_{2\text{-jet}}}$$

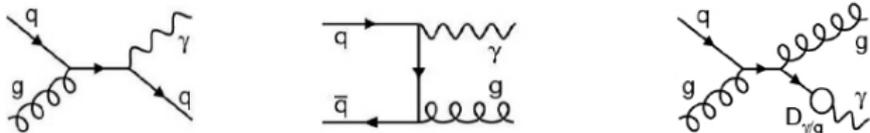
Test of pQCD and  $\alpha_S$  independent of PDFs: 2 momentum scales

- $p_{T\text{max}}$  common for both  $\sigma_{2\text{-jet}}$  and  $\sigma_{3\text{-jet}}$
- $p_{T\text{min}}$  - scale at which the 3<sup>rd</sup> jet is resolved ( $\sigma_{3\text{-jet}}$  only)

sensitive to  $\alpha_S$  at the scale  $p_{T\text{max}}$



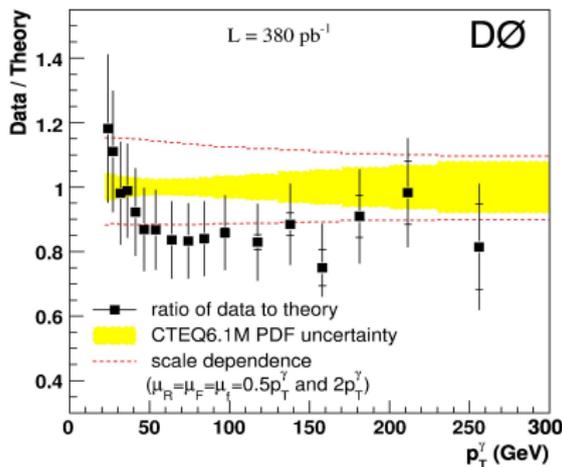
# $\gamma$ + Jets



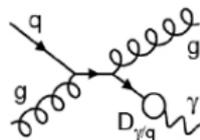
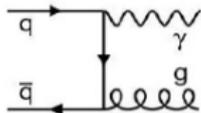
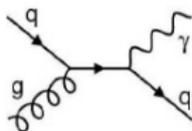
Direct photons emerge unaltered from the scattering process  $\rightarrow$  direct probe of hard scattering dynamics + potential sensitivity to PDFs

DØ published several measurements:

- Isolated photon cross section



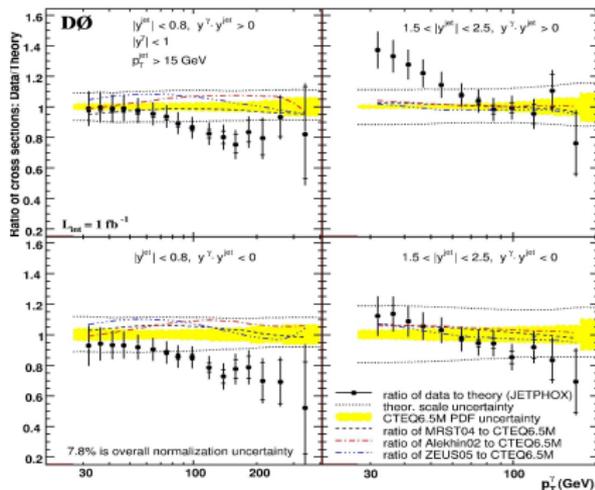
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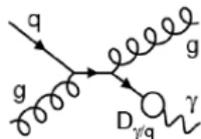
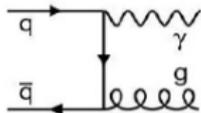
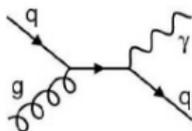
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PLB 639, 151 (2006), PLB 658, 285 (2008), PLB 666, 2435 (2008), PRL 102, 192002 (2009)

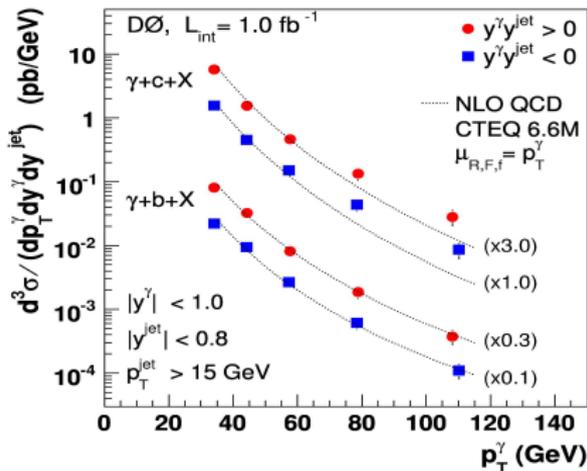
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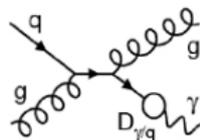
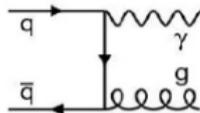
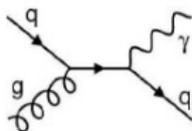
DØ published several measurements:

- Isolated photon cross section
- Photon+jet
- Photon+heavy flavor jet



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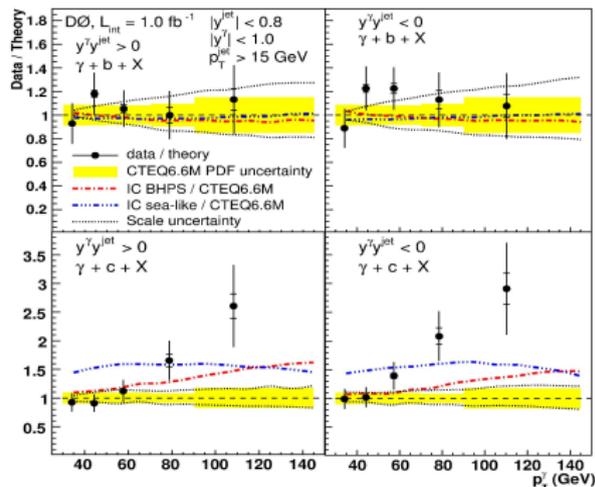
# $\gamma + \text{Jets}$



Direct photons emerge unaltered from the scattering process  $\rightarrow$  direct probe of hard scattering dynamics + potential sensitivity to PDFs

$D\emptyset$  published several measurements:

- Isolated photon cross section
- Photon+jet
- Photon+heavy flavor jet
- All with data/theory discrepancies - missing theory piece?



PLB 639, 151 (2006), PLB 658, 285 (2008), PLB 666, 2435 (2008), PRL 102, 192002 (2009)

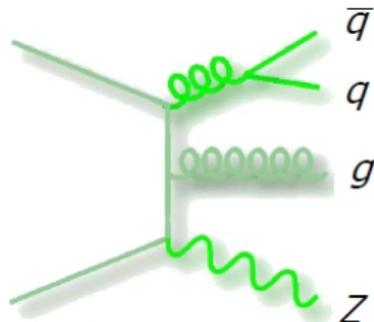
# $W/Z + \text{Jets}$

- Use  $W/Z$  bosons as a probe of QCD.
- Concentrate on high  $p_T$  final states = domain of pQCD
- These final states are backgrounds to many SM and BSM processes

## Current status:

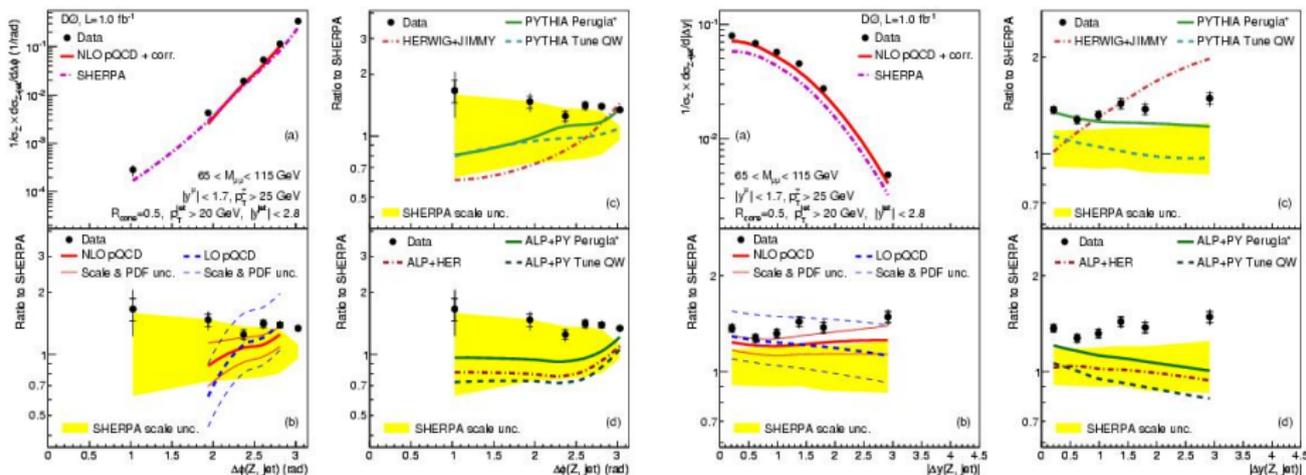
- pQCD
  - LO -  $W/Z + 1-6$  partons
  - NLO -  $W/Z + 1-2$  partons
  - new NLO  $W + 3$  partons
- Monte Carlo generators
  - LO  $2 \rightarrow 1, 2 + \text{PS}$  (PYTHIA, HERWIG)
  - LO  $2 \rightarrow 1 - 6 \text{ ME} + \text{PS}$  (ALPGEN, SHERPA)

→  $Z + \text{jets}$  final state used for testing perturbative QCD and for tuning Monte Carlo generators



# Z/ $\gamma^*$ + Jet + X Angular Distributions

- Reasonable agreement between data and NLO, with significant improvement of NLO compared to LO
- Event generators tend to have normalization and shape differences  $\Rightarrow$  MC tuning



PLB 682, 370 (2010)

# Summary of Experimental Results

- Inclusive jet cross section - agreement over many magnitudes with NLO pQCD, used to constrain PDFs (MSTW2008) and to measure the strong coupling constant  $\alpha_S$
- Dijet final state - measured angular distributions  $\Delta\phi$ ,  $\chi_{\text{dijet}}$ , dijet invariant mass - all in good agreement with NLO
- Multijet states - three-jet cross section and R3/2
- $\gamma$ +jets states - several measurements - all with data/theory discrepancies
- $W/Z$ +jets used to tune MC generators

# Conclusions

- Large Run II dataset offers many possibilities for jet/QCD studies (only a fraction mentioned in the talk)
  - <http://www-d0.fnal.gov/Run2Physics/WWW/results.htm>
  - [http://www-d0.fnal.gov/d0\\_publications/d0\\_pubs\\_list\\_runII\\_bytopic.html#qcd](http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#qcd)
- DØ uses midpoint jet algorithm with jet energy scale calibration uncertainty below 2%  $\Rightarrow$  significant reduction of systematic uncertainties in many measurements
- NLO pQCD provides good description for most of the measurements
- There are final states/kinematic regions where the Tevatron will continue to dominate over the LHC
- Still expect many new results before the end of the Run II